U.S. MAGNET DEVELOPMENT PROGRAM

Nb_3Sn cos-theta magnets: program status and next steps

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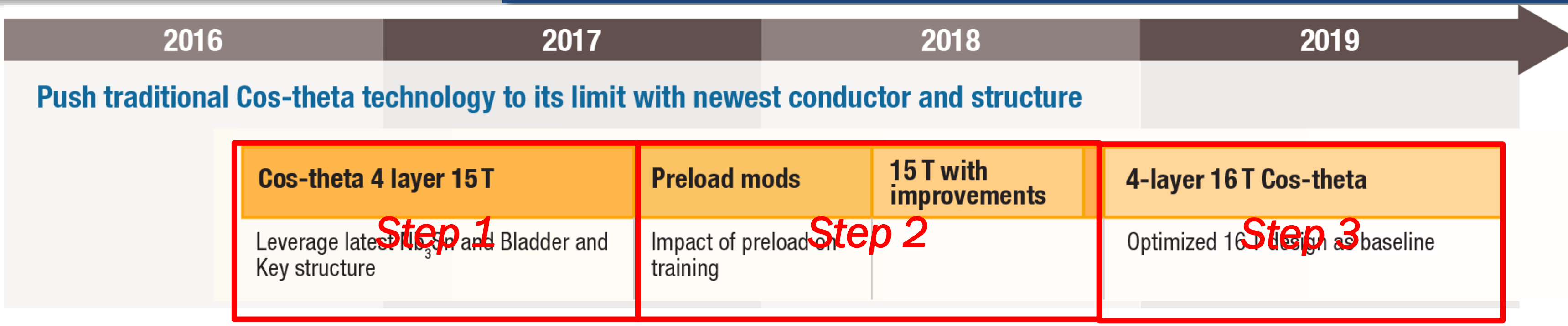
This presentation address questions in the Charge to “Nb_3Sn magnets” session

1. What are the near-term needs for testing the Cos-theta magnet? Who is responsible for the magnet preparation? Who is responsible for testing? What support is needed, and who’s help is requested?
2. What are the scenarios for the 15 T, and how do we respond to the various cases? What spares do we have, and are there investments we should make now, or plan for in the near future, to maximize the value of the 15 T investment?
3. What design efforts are being/should be undertaken in the near-term for Nb_3Sn magnets? What are the figures-of-merit for designs? What "technology“ developments/data are most valuable in developing next designs (materials properties? Modeling capabilities? Test data analysis?)
4. We need to plan a workshop (recommendation from the GARD comparative review) once sufficient data is obtained from the Cos-theta and CCT efforts. What criteria should trigger that workshop?

MDP Nb_3Sn cos-theta magnet R&D plan (three steps) is being executed



- Step 1: 15 T dipole demonstrator design.
  - explore the target field and force range
  - serve as a technical and cost basis for comparison with new concepts
  - opportunity for program integration, particularly in the area of support structure design, and for exploration of various support structures.
- Step 2: A successful series of magnets will provide a platform for performance improvement by integrating the outcomes of the Technology Development program.
- Step 3: 16 T cos-theta design to explore the limit of Nb_3Sn in this geometry.

Step 1: 15 T Dipole design is complete and all components fabricated

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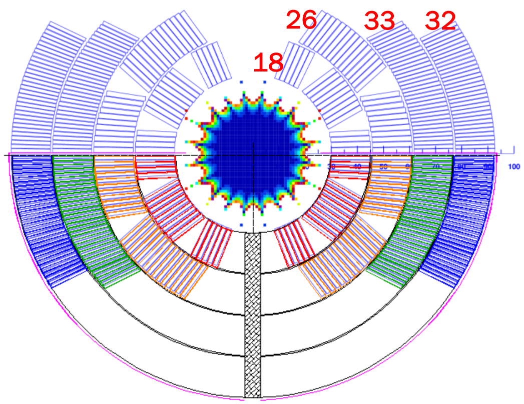
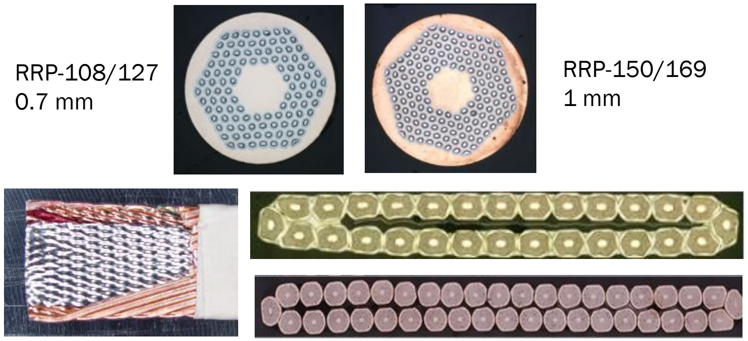
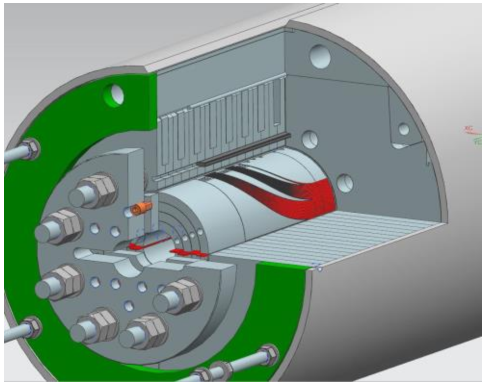
- Coil:
  - 60-mm aperture, 4-layer graded coil
  - W_{sc} = 68 kg/m/aperture

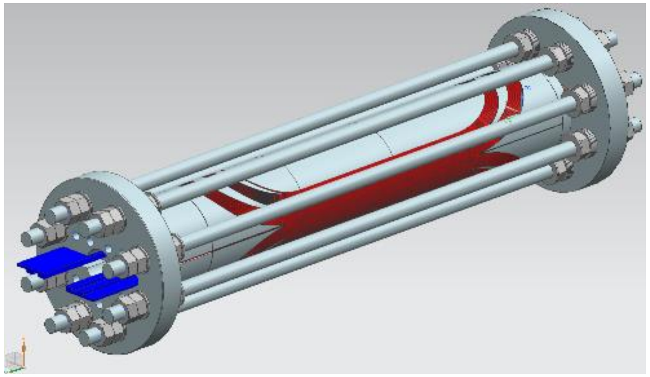


- Cable:
  - L1-L2: 28 strands, 1 mm RRP150/169
  - L3-L4: 40 strands, 0.7 mm RRP108/127
  - 0.025 mm x 11 mm SS core
  - Insulation: E-glass tape

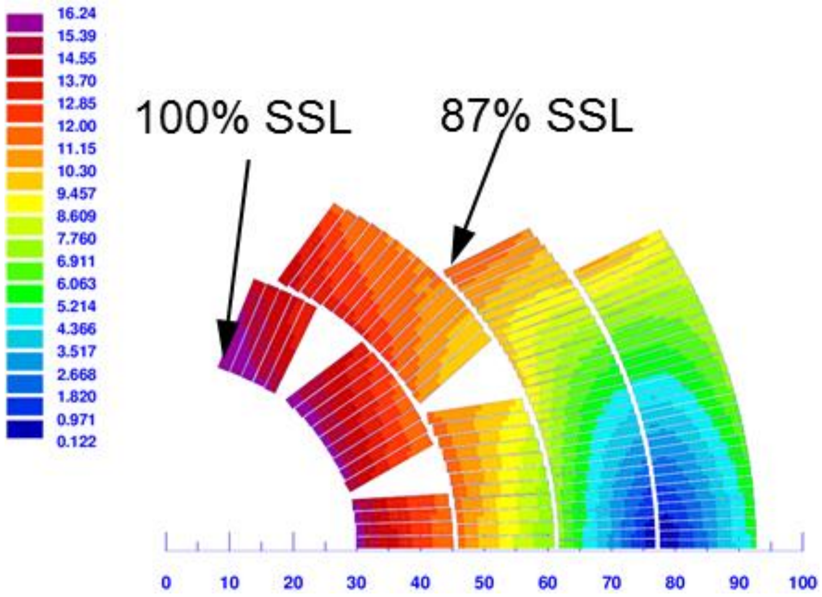


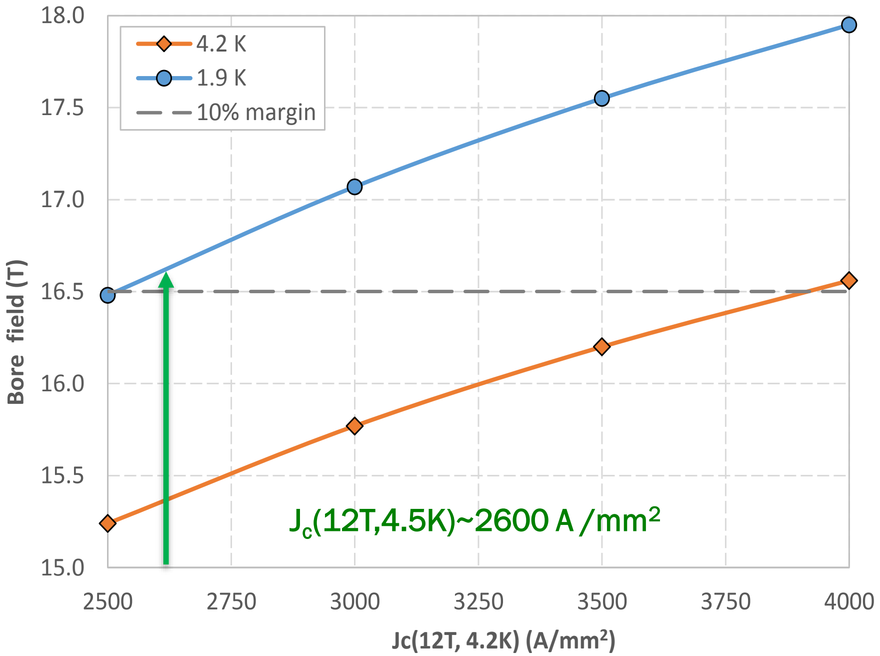
- Mechanical structure:
  - Thin StSt coil-yoke spacer
  - Vertically split iron laminations
  - Aluminum I-clamps
  - 12-mm thick StSt skin
  - Thick end plates and StSt rods
  - Cold mass OD<610 mm





Magnet conductor limit close to 17 T at 1.9 K

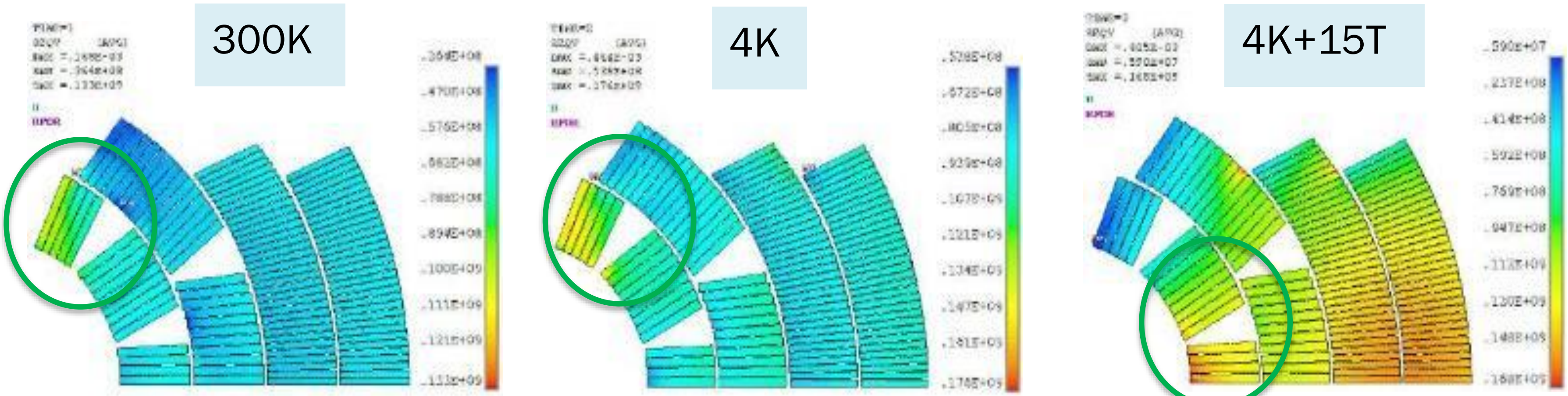




Magnet conductor limit for the wire J_c(12T,4.2K)~2.65 kA/mm^2:

- B_{ap}=15.3T @4.5K
- B_{ap}=16.7T @1.9K

Magnet mechanical limit is 15 T. It is still larger than present record field.



S_{eqv}=133 MPa
Limit 150 MPa

S_{eqv}=176 Mpa
Limit 200 MPa

S_{eqv}=168 Mpa
Limit 200 MPa

- **Magnet design limit is determined by the coil maximum stress and pole turn separation from the pole (independent FNAL and FEAC analysis)**

Mechanical limit for this design is 15 T!

Record Nb_3Sn dipole magnets:

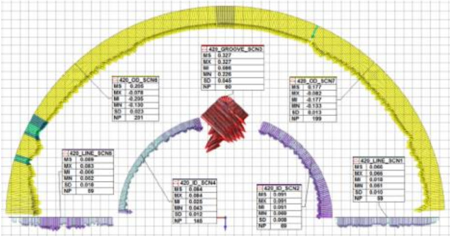
- D20 (LBNL, 1997): B_{max}=13.5 T @1.9K
- HD2 (LBNL, 2008): B_{max}=13.8 T @4.5K
- FRESCA2 (CERN, 2018): B_{max}=14.6 T @1.9K

Fabrication of 2 IL and 2 OL coils is complete

Coil winding and curing using ceramic binder

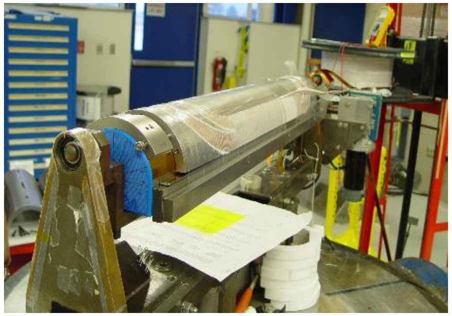
Coil and samples reaction

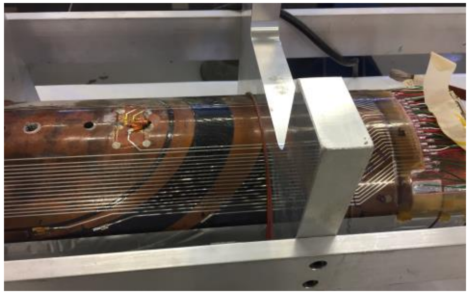
Coil lead splicing and epoxy impregnation



Coil size control for coil pre-load
Accuracy ~10 microns

Coil instrumentation

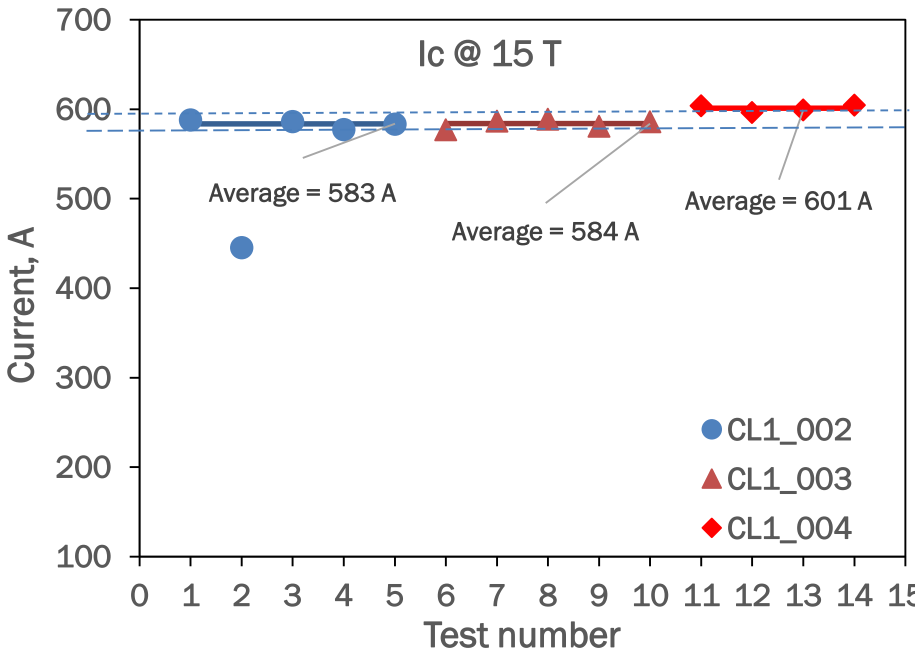




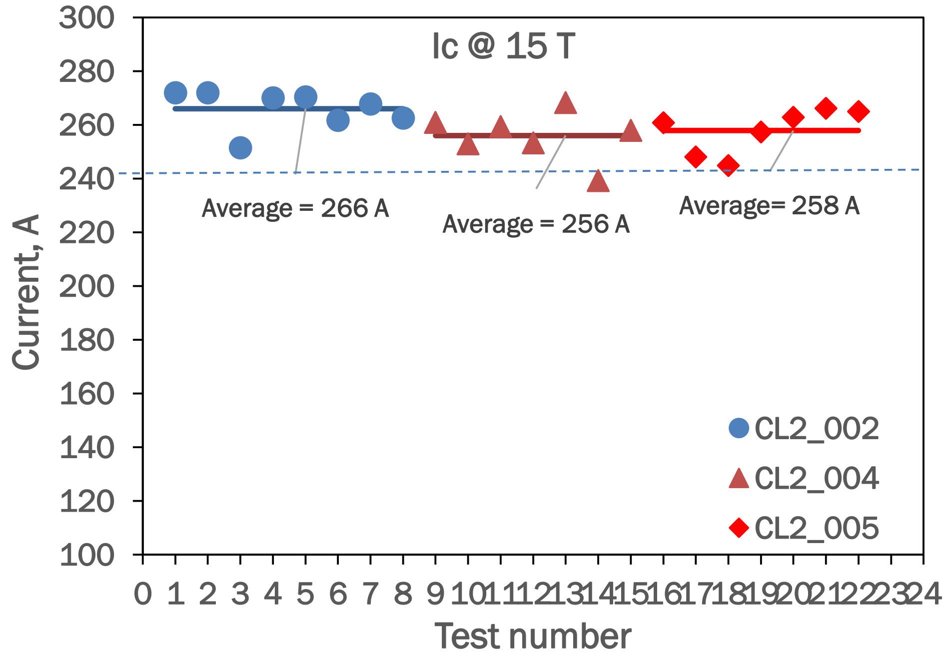
- Coil fabrication, measurement and instrumentation time ~3 months
- IL spare coil was wound and reacted
- OL spare coil – waiting for the cable and coil parts

Witness sample data are close to the target I_c

IL coils

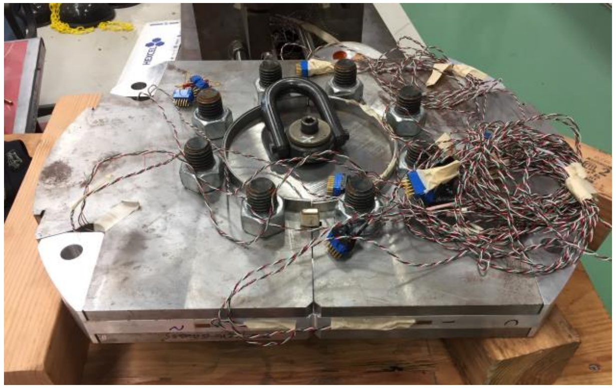


OL coils



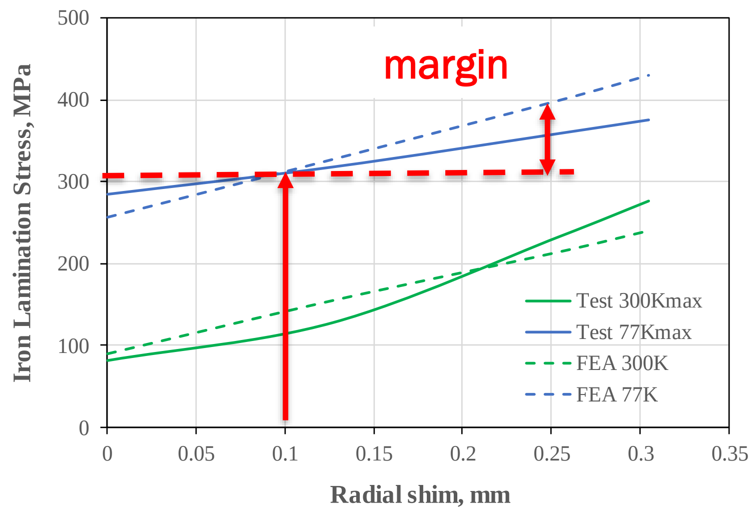
- **Good reproducibility of witness sample data for both IL and OL coils**

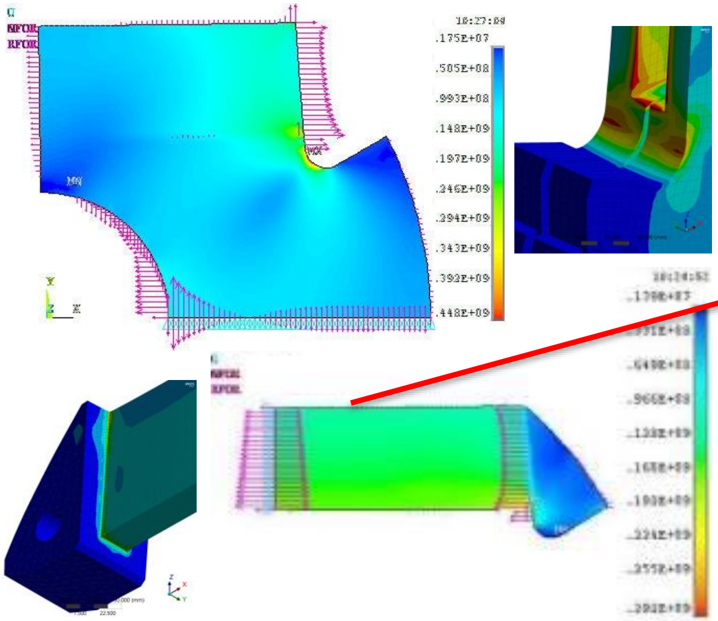
Tests of several short MM complete

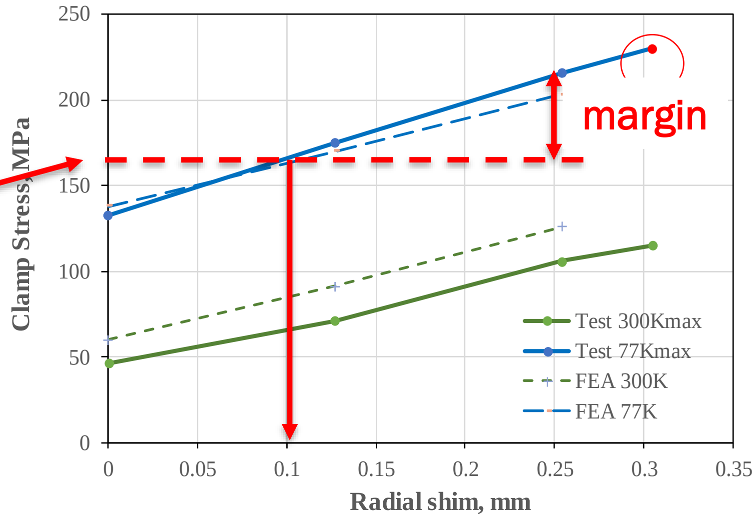


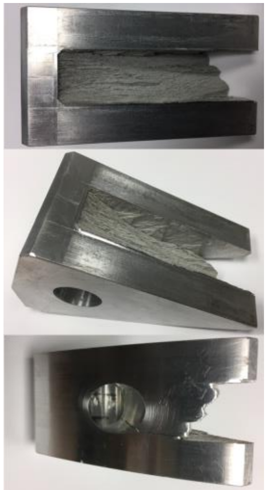
Goals:

- Test brittle yoke and clamps
- Validate the mechanical analysis
- Develop the coil pre-stress targets

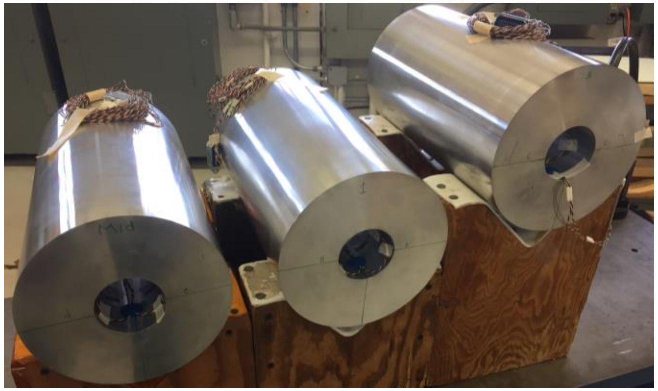








Full-scale mechanical and technological models assembled and tested



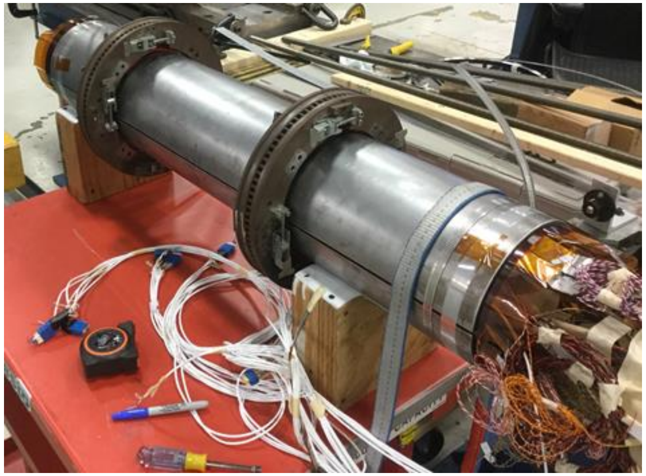
Goals:

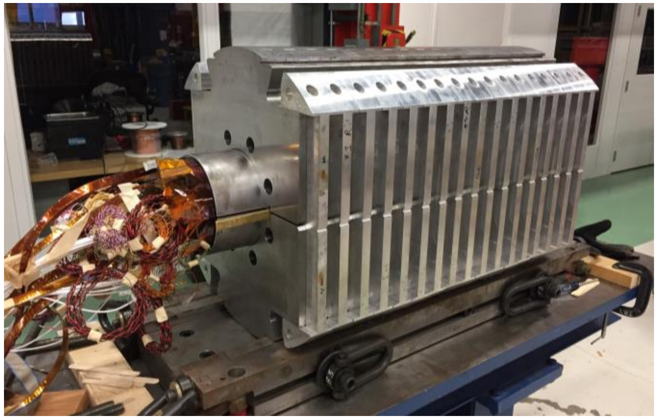
- Test all structural components and tooling
- Develop the magnet assembly plan

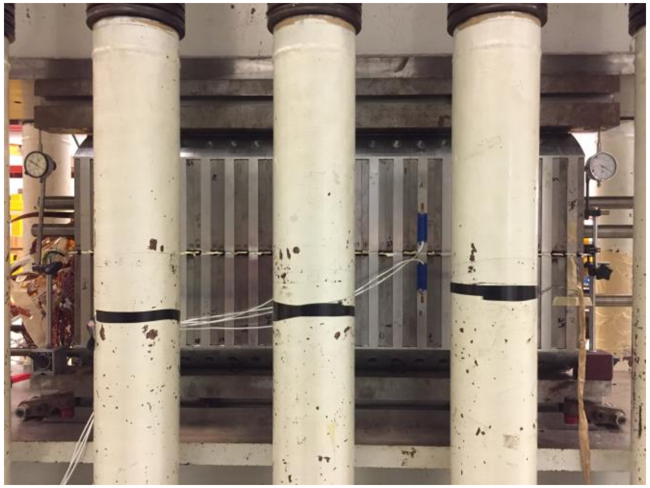
Assembly readiness review was conducted on October 5, 2018

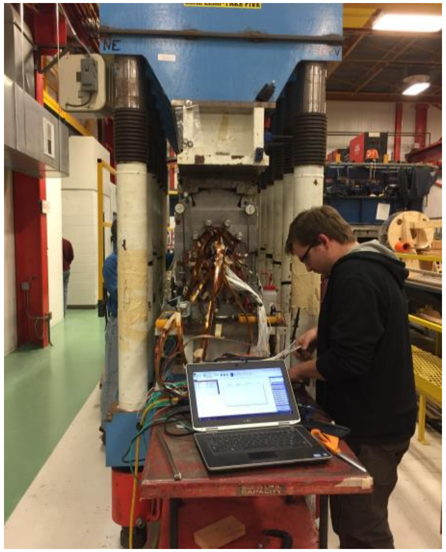
- 5th 15 T dipole review
- Review committee: G. Chlachidze (chair), G. Ambrosio, F. Nobrega, D. Cheng (LBNL), S. Caspi (LBNL)
- Review questions:
  1. Are the coils instrumented, measured and ready for assembly?
  2. Is the mechanical structure tested and ready for assembly?
  3. Is the magnet instrumentation plan available and documented?
  4. Are the magnet assembly target parameters formulated and justified?
  5. Is the magnet assembly plan sound and well understood?
  6. Are the main risks identified and their impact understood?
- Review report (October 17, 2018):
  - 10 comments and 6 recommendations
  - All the comments and recommendations were carefully studied and addressed before magnet assembly

Magnet assembly and test preparation are in progress









- Coil matching and shimming
- Coil-yoke assembly
- Coil massaging in press
- Coil assembly shimming
- Yoke clamping
- Skin welding
- End pre-load
- Instrument. connectors
- Final tests
- Test readiness review – end of February

Step 2: Preload modification, 15 T dipole improvement

- 15 T dipole 1st test scenarios:
    1. Magnet reaches the target field 14 T => magnet re-assembly and second test with higher pre-stress
    2. Magnet performance is limited by a coil => re-assembly with spare coil and optimized pre-load, second test

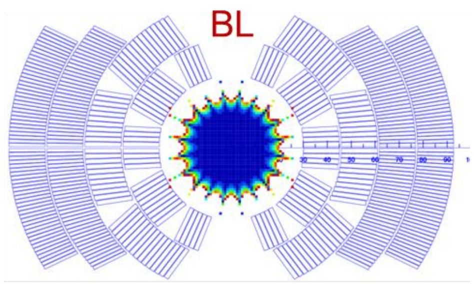
- Spare coil status:
    - Since the maximum values of B and stress are in the IL, the IL coil has higher priority
    - IL spare coil was wound and reacted, and is being prepared for impregnation - will be available in March
    - OL spare coil - waiting for the cable and coil parts – will be available in July
    - Additional coils
        - IL coil parts – 1 additional set is available from CERN
        - 28 strand cable - 2 UL of the are available
        - need traces

- Second magnet test is expected in October 2019

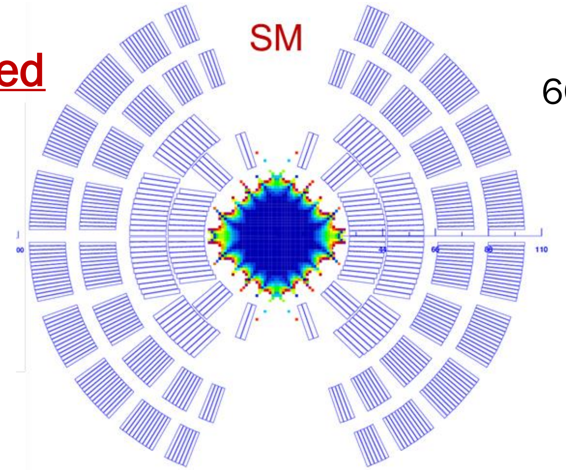
Step 3: Conceptual design and analysis of 4-layer 16 T cos-theta dipole complete

1. Conceptual design studies are complete including magnetic and mechanical analysis

60 mm aperture
B_{des}~15 T



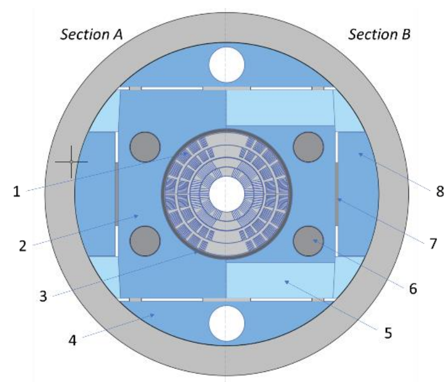
SM is needed

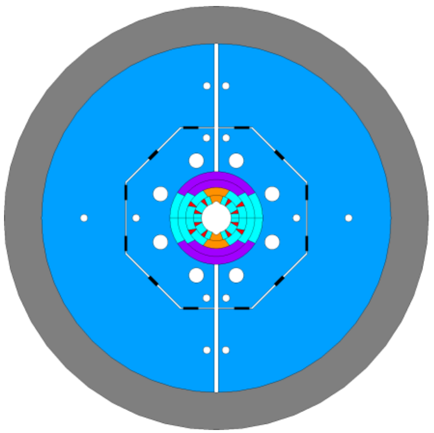


60 mm aperture
B_{des}~17 T

2. Two mechanical structures have been developed and analyzed

- Utility structure (M. Juchno)
  - OD=750 mm, 75 mm Al shell
- Compact structure for VMTF (FNAL)
  - OD=630 mm, 55 mm Al shell, Al clamps





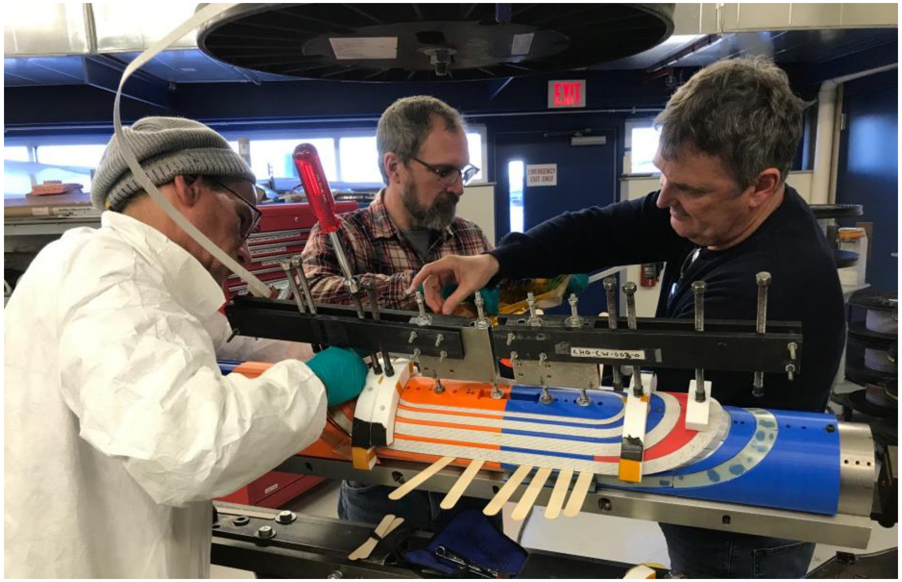
2-layer coil design with stress management developed

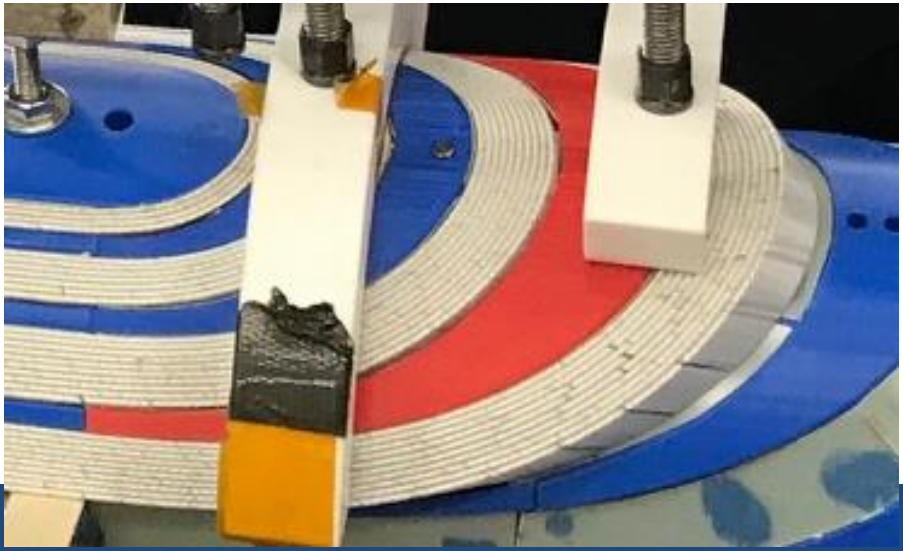
Justin Carmichael (FNAL-ANL)

- Two possible end designs and technologies
  - Design 1: winding with spacers (RE)
  - Design 2: winding into slots (LE)
- Plastic parts were produced using 3D printing technology
  - this technology is used also with SS and other materials

SM coil technology is been verified using practice coil

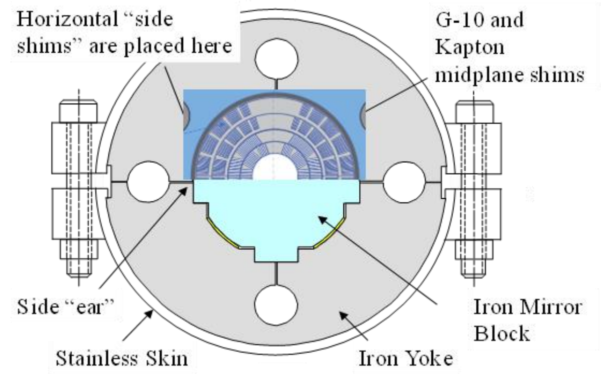
- Goals: test new parts and new winding technology
- Findings:
  - Faster and simpler winding
    - coil layer winding in 2 days instead of 5 days
  - Coil curing is not needed
    - save additional 2-3 days per layer
  - Excellent winding quality
  - Excellent body-end transitions on both LE and RE
  - No large pockets for epoxy accumulation
  - Controlled gaps for coil expansion after reaction
- Next:
  - finish L2 winding
  - coil impregnation with epoxy

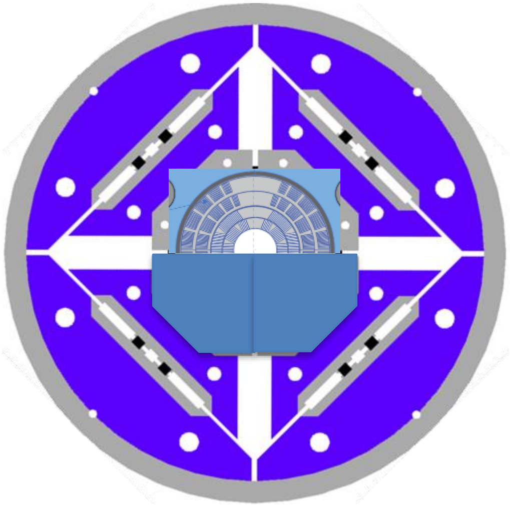




Next steps: SM coil technology test using dipole mirror structure

- Dipole mirror structure:
    - Modification of HQM mirror or HQ structure
- Fabricating and testing SM coil in a dipole mirror configuration
    - Coil part procurement – April-May
    - Reaction-impregnation tooling modification – May-June
    - Coil fabrication – June-July
    - Mirror structure modification – July-September
    - Mirror assembly and test preparation – October-November
    - Mirror test – December 2019
    - Total task duration ~9 months





Modification of HQ or HQM structures (both are available)

Evolution of cos-theta Nb_3Sn dipoles with stress management

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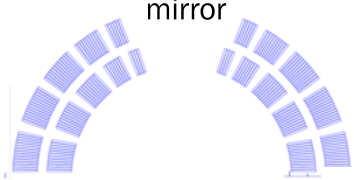
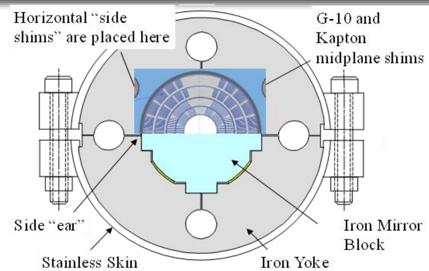
December 2019

120-mm 2L SM dipole mirror

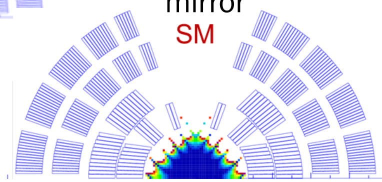




+6 months

60-mm 4L SM dipole mirror

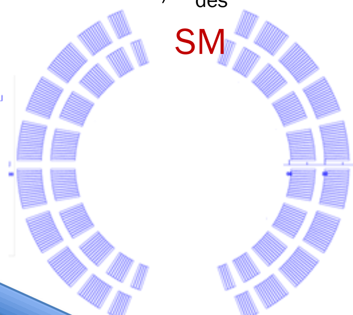
SM

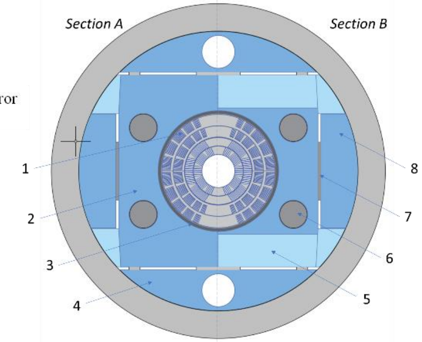


+6 months

120 mm, B_{des}~11 T

SM

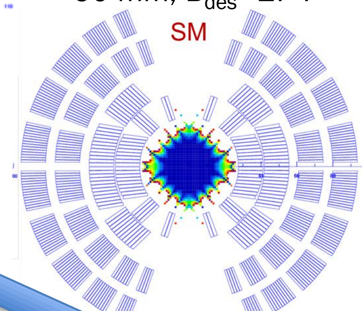


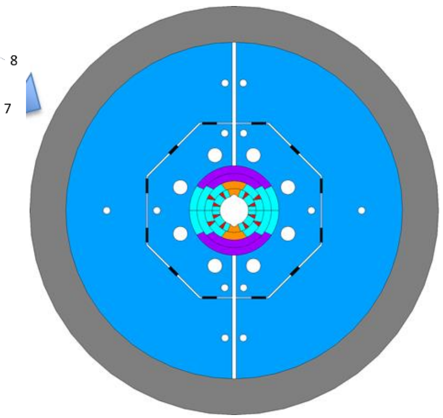


+6 months

60 mm, B_{des}~17 T

SM

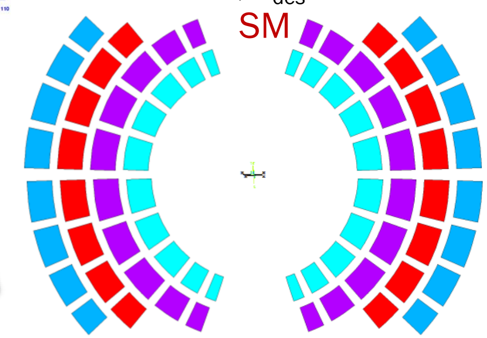




+12 months

120 mm, B_{des}~15 T

SM



Goals:

- continue addressing key MDP driving questions 1-9
- develop Nb_3Sn dipole to test cables, HTS inserts, etc. for MDP and other programs
- fast turnaround time

Conclusion: Good progress since CM2

- Step 1
  - 15 T dipole is a challenging and important MDP milestone to understand limits of Nb_3Sn accelerator technology - integrated international effort with CERN
  - Fabrication of 15 T dipole demonstrator is in progress
    - Fabrication of 2 IL and 2 OL coils is complete
    - Short and long MMs have been assembled and tested
    - Magnet assembly is in its final stage
  - Magnet test is expected in March 2019
- Step 2
  - IL spare coil was wound and reacted, impregnation and instrumentation in Jan-March
  - OL spare coil – waiting for the cable and end parts, coil fabrication in April-June
  - Second magnet test in October 2019
- Step 3
  - Design studies of 16 T dipole with 60-mm aperture is complete
    - 120-mm aperture SM coil design is complete
    - Large-aperture SM coil technology development has started
- Next steps:
  - continue large-aperture SM cos-theta coil technology development to test SC cables and HTS inserts
- Magnet workshop – end of 2019, after 15 T dipole 2nd test

What has been done since previous CM?

	Design studies	Infrastructure	Magnet & tooling design	Parts, tooling fabrication	Coil fabrication & instrument.	Mechanical Models	Magnet assembly
MDP CM2	• Magnetic and mech. design and analysis of High-Field Nb_3Sn cos-theta dipole with stress management (MT-25).	• Complete	• Complete	• Complete	• OL – 3 coils wound-cured, 2 damaged, 1 prepared to impregnation • IL – 2 coils wound-cured • Instrumentation: not started • Witness sample test	• all components and instrumentation complete • test has started • yoke assembly started	-
MDP CM3	• Magnetic and mech. analysis of a 17 T Nb_3Sn accelerator dipole and new mechanical structure (IPAC2018) • Magnetic and mechanical analysis of large-aperture high-field Nb_3Sn dipole magnets (IPAC2018)	• New winding table inst. and commissioning • Curing press repair and recommissioning • Reaction oven and retort commissioning • Modification of press assembly area (safety) • Curing tooling modification (review recomm-endation)	• New Al clamps • Iron lams modification • Magnet suspension modification (for new clamps) • Iron filler modification for instrumentation • 120-mm coil with stress management • L3/L4 impregnation tooling modification	• New Al clamps • Iron lams modification • Parts for magnet suspension system • Iron filler cut • Plastic parts for 120-mm coil with SM • Thin shell technology development and shell fabrication	• 2 IL and 2 OL wound-cured-reacted-impregnated, measured and instrumented • IL spare coil wound-cured-reacted (prepared for impregnation) • SM practice coil winding started • All coils instrumented with VT, SG and QH • Witness sample tests	• SMM: tests with old and new Al clamps • LMM: Tests with Fuji films and aluminum dummy coils, Iron lams sorting • Assembly and Tests of Mechanical Models of the 15 T Nb_3Sn Dipole Demonstrator (ASC2018) • Winding 120 mm practice coil with SM	• Magnet assembly in progress • Coil size test and matching • Ground wrap and additional heaters • Assembly with iron yoke • Coil massaging and clamping to select coil-yoke shim